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Identification of light availability in different sweet cherry orchards under cover by using non-destructive measurements with a Dualex™

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ABSTRACT

Changing climatic conditions makes the development of cultivation strategies for protected cherry cultivation necessary. The objective of the present study was to investigate physiological processes in connection with light availability in different planting systems under cover using a Dualex™ for non-destructive measurements. Hence, cherry trees were either trained as hedgerows, i.e. the most dense planting ([2.35 m*2]*1.5 m), or trained as spindles (2.70 m*2.0 m; 1.75 m*2.9 m) and grown under cover or in the open field at Klein-Altendorf near Bonn, Germany. There was no difference in leaf area between the plantings. Non-invasive measurements with the Dualex™ (Force A, France) showed that a larger relative leaf chlorophyll content (Chl = 30–33) in the hedgerow trees under crop cover as a result of less light than in the open field-grown leaves with less chlorophyll (ChI = 26–28). Similarly, the flavonoid index (Flav), as a relative measure of the epidermal flavonoids and light condition, was generally lower under crop cover and lowest in the hedgerow trees on the adaxial leaf side with Flav = 1.4–1.5 relative to 1.6–1.8 in the open field, but always maintained these high values above the critical light level of 1–1.2. Non-invasive SunScan measurements showed light reductions of up to 80% inside the canopy of the dense hedgerow trees under cover in line with the lowest values for Flav and ChI. Although the largest yield per tree was obtained in the planting system with the best light conditions (1.75 m*2.9 m), the largest yield per acreage was found in the most dense planting (2.7 m*2.0 m) with hedgerows under cover as an ideal combination of a high yield and fruit quality with good light availability. Overall, our results showed that light availability depends on crown structure, planting system and tree density. The indices Flav and ChI offer the possibility to evaluate the light conditions in an orchard easily and to give a recommendation for an optimized growing system.

1. Introduction

Climate change brings about earlier and more intense solar radiation in spring (Legave et al., 2012). As a result, cherry can now be forced under protected cultivation to enhance flowering in spring and produce an earlier crop of high fruit quality and value (Schmitz-Eiberger and Blanke, 2012; Overbeck et al., 2017). The question remains whether trees with different training, pruning and spacing under protected cultivation, however, may still suffer from light deprivation in different parts of the tree canopy in early spring and which countermeasures are required.

A new sensor (Dualex™; Goulas et al., 2004) offers a non-invasive method to examine light limitation in a tree canopy based on the Flavonoid Index (Flav), which is lower under light deprivation. Measured concomitantly, the Chlorophyll Index (Chl) and the Nitrogen Balance Index (NBI) describe the relative chlorophyll and nitrogen content of the same leaves. As plant productivity relies on net photosynthesis, which may be limited by various factors such as temperature, water and light, the latter is the essential source of energy and external signal for regulating developmental processes in plants (Tobin and Silverthorne, 1985).

The use of protective cultivation (hail net, shade net, polytunnel) is increasing in many fruit crops worldwide including apple and cherry, but often associated with light as a limiting factor e.g. in the fruit growing belt at 50°N throughout Europe.

This new sensor technology enables a non-invasive detection and insight into light limitations of different planting systems of fruit crops grown under crop cover and at critical times (e.g. during fruit set) based on relative changes in the light dependent biosynthesis of leaf flavonoids and chlorophyll. The portable Dualex™ instrument determines the

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polyphenolic compounds in leaves by measuring the UV absorbance of the leaf epidermis by double excitation of chlorophyll fluorescence. Goulas et al. (2004) described the working principle based on the advantage of a feedback loop that equalizes the fluorescence level induced by a reference red light to the UV-light-induced fluorescence level. In their study on muskmelon, Pradella et al. (2014) compared different optical sensors to assess crop nitrogen status and showed that all measurements were sensitive to nitrogen content.

The novelty of this research is the evaluation of the relationship between these different non-destructively measured parameters FIav, ChI and NBI of the Dualex™ and the distribution of the incident light within the tree canopy to compare different growing systems and tree training for an optimal fruit production system. In the apparent absence of such studies using the Dualex™ with fruit trees and the flavonoid and chlorophyll status of leaves to obtain a relationship to light availability and light limitation, the objective of the present work was to examine whether cherry trees under protected cultivation are subject to a) light limitation and b) chlorophyll limitation during the important and critical phase of fruit set and fruit development. This physiological information may aid to develop cultivation strategies for protected cherry cultivation e.g. pruning, rootstock selection, plant spacing and tree training.

2. Material and methods

2.1. Orchard and experimental design

Six-year-old sweet cherry (*Prunus avium* L.) trees of cultivar 'Samba Sumste','Bellise Bedel' and 'Rita' on dwarfing rootstock GiSelA 3 were grown at Campus Klein-Altendorf (latitude 50.5°N), University of Bonn, Germany. Half of the cherry trees were covered with a polyethylene plastic UV M42 Window plus (180 μ) (folitec Agrarfolien-Vertriebs GmbH, Westerburg, Germany) at the beginning of April, utilizing natural solar radiation for heating. Drip irrigation was used to supply the plants with water. The cherry trees with three training systems were planted at three planting densities (Table 1). The research block consisted of five replicated plots of ca 2000 m^2. Three plots were covered and another two plots were left without cover served as control. Each training system comprised an area of 561 m^2 including tall spindle axe (trees were spaced 2.7 m × 2.0 m, two rows per subplot, 1023 trees/ha, cultivars were clustered in five trees), another tall spindle axe (trees were spaced 3.00 m × 2.9 m, two rows per subplot, 706 trees/ha). The three cherry cultivars were clustered in three trees and a super spindle (slender axe) (trees were spaced 2.35 m × 1.5 m, three rows per subplot, 2000 trees/ha, cultivars were clustered in six trees) (Table 1). In the last subplot, cherry trees were pruned mechanically in spring, at a 83° cutting angle and 0.45 m distance from the trunk. The clustered trees were randomized in the subplots. All trees rows were arranged in north-south orientation for utilization of solar radiation.

2.2. Measurement of light penetration into the tree canopy

Light penetration was measured at two heights, under the tree canopy and in the middle of the tree crown: 0.5 m and 1.5 m above ground using a SunScan CanopyAnalysis System (Delta T Devices, Cambridge, U.K.). At both heights, eight measuring positions were employed every 45° of the 360° degree crown circle, going out from the trunk.

The 64 light sensors of the SunScan measured individual levels of photosynthetic active radiation (PAR 400–700 nm), which are transmitted to a PDA and expressed as $\mu mol\, m^{-2} s^{-1}$. A beam fraction sensor (BFS), which monitored the incident light outside the canopy between the tree rows served as reference. This BFS consists of different photodiodes to measure the diffuse and direct components of PAR.

To obtain constant light conditions, light measurements were conducted on overcast days with diffuse light conditions on 17 and 18 June and on 8 July 2014. Results are expressed as percentage of light in the tree crown relative to the incident light.

Table 1
Experimental design at Campus Klein-Altendorf, near Bonn, Germany.

Treatments	Tree spacing	Tree rows	Cover	Tree design	Trees/ha
T1	2.70 m × 2.0 m	2	yes	spindle	1023
T2	1.75 m × 2.9 m	2	yes	spindle	706
T3	(2.35 m*2) × 1.5 m	3	yes	Super slender spindle	2000
F2	2.70 m × 2.0 m	2	no	spindle	1023
F3	1.75 m × 2.9 m	2	no	spindle	706

2.3. Optical sensor for measurement of relative chlorophyll and flavonoid content

Dualex™ (FORCE-A, Orsay, France) was used to measure non-destructively the relative chlorophyll and flavonoid content of leaves based on the chlorophyll fluorescence excitation spectra (Cerovic et al., 2005). It operates with an excitation UV beam at 357 nm (absorption maximum for flavonoids) and a red reference beam at 650 nm (absorption maximum for chlorophyll). Foliar flavonoid content was estimated as Log (Infrared Fluorescence exited by Red/Infrared Fluorescence exited by UV), whereas the relative chlorophyll content was measured as (Infrared transmittance – Red transmittance) divided by Red transmittance. Cherry leaves on two-year-old wood in the (shaded) centre of the canopy from the north side of the tree were measured three times (15.4., 06.05. and 27.05.2014) during the critical phase of fruit development. The flavonoid data are means of measurements from the adaxial and abaxial side of 20 leaves of every treatment and cultivar; the chlorophyll data and the nitrogen balance index are representative for the adaxial side of the leaves.

2.4. Leaf area and specific leaf weight

Five leaves were chosen of four trees for each cultivar and planting system; leaves were picked in the centre of the canopy on two-year-old wood from the north side of the tree because of the N-S tree row orientation and potentially poor light conditions.

The five leaves of each tree, representative of the cultivar and the planting system, were weighed and the specific leaf area was calculated using the weight of 1.3 cm^2 diameter leaf discs. Trees served as replicates resulting in 20 samples.

2.5. Statistics

All experimental data were analyzed using the statistic software SPSS 21.0 (IBM, Armonk, NY, USA). Means were compared by Games-Howell multiple range test after data were checked for normal distribution and variance homogeneity and failed the latter. The statistical analysis was performed by one-way ANOVA at a probability level of 95% to indicate significant differences between the different planting systems. Flavonoid index, nitrogen balance index and chlorophyll index were averaged from replicate measurements on 20 leaves. Both other parameters were presented as four replicates for each cultivar and treatment.

3. Results

3.1. Incident light in different planting systems

Incident light under cover was reduced up to 29% of incident and diffuse light and PAR up to 58% on a cloudy day during fruit development (data not shown). Depending on tree crown structure with a higher volume of leaves and tree branches at the bottom and tapering

Table 2
(a) Light measurements at eight positions under the tree crown in 0.5 m height for trees in the different planting systems (treatments). All results are given in percentage total light in the tree crown in relative to the total incident light. (n = 4). (b) Light measurements at eight positions in the middle of the tree crown in 1.5 m height for trees in the different planting systems (treatments). All results are given in percentage total light in the tree crown in relative to the total incident light.

(a)
under the tree crown (0.5 m height)

Treatment	West	Northwest	North	Northeast	East	Southeast	South	Southwest
'Samba'								
T1	42,83	41,90	33,88	35,23	39,96	37,00	29,79	32,03
T2	36,14	39,63	33,47	36,91	49,36	35,86	32,79	32,03
T3	33,75	30,67	19,31	24,44	26,30	23,52	17,54	29,25
F2	36,41	37,39	35,09	45,54	43,36	44,44	42,94	37,96
F3	40,61	44,07	43,58	52,39	55,49	52,04	44,49	43,17
'Bellise'								
T1	21,23	21,64	23,55	27,88	26,61	23,44	21,13	26,58
T2	25,88	19,88	27,82	36,54	35,30	29,67	22,04	23,34
T3	24,90	19,93	11,59	21,43	24,19	17,71	12,26	22,03
F2	22,61	27,76	30,47	28,40	37,18	37,01	23,24	21,01
F3	30,63	25,53	25,58	29,61	41,05	38,64	32,01	33,75
'Rita'								
T1	32,43	30,27	24,59	26,11	27,34	26,51	33,04	32,39
T2	38,88	43,41	43,15	47,15	37,41	44,96	37,94	31,63
T3	24,53	22,01	13,56	27,36	27,84	23,77	11,28	19,50
F2	30,92	30,83	32,76	35,94	38,00	35,56	27,86	26,90
F3	43,14	42,79	39,07	42,12	50,39	54,79	49,08	40,18

(b)
middle of the tree crown (1.5 m height)

Treatment	West	Northwest	North	Northeast	East	Southeast	South	Southwest
'Samba'								
T1	58,09	60,54	44,60	43,28	45,93	46,78	37,93	47,46
T2	53,99	48,16	36,78	51,91	50,00	64,08	47,05	49,71
T3	36,78	36,70	13,29	22,29	28,92	21,42	14,52	30,56
F2	40,90	43,78	40,93	66,18	49,06	58,46	51,78	43,18
F3	53,52	53,40	56,37	53,14	66,94	56,05	54,85	57,72
'Bellise'								
T1	35,62	40,06	41,52	35,68	37,58	27,59	29,25	28,55
T2	41,09	47,36	49,56	41,68	49,19	42,83	39,80	34,34
T3	26,38	27,74	7,89	20,81	27,60	21,72	10,81	25,36
F2	42,19	40,71	38,37	48,79	49,36	58,87	47,40	49,72
F3	48,02	46,98	50,35	46,20	40,59	47,53	39,91	47,57
'Rita'								
T1	53,00	50,01	50,58	49,83	44,59	46,69	49,69	52,31
T2	58,55	64,41	56,86	66,91	68,76	68,09	57,04	59,74
T3	33,36	29,91	14,01	32,49	38,50	29,65	10,27	19,58
F2	57,32	55,19	51,63	60,22	60,01	63,26	59,88	62,46
F3	55,80	58,53	46,07	58,09	56,66	62,24	60,40	66,13

Table 3
Average yield per tree of cherry trees who are growing in different treatments e.g. with different tree spacings and with cover and without cover, mean ± SE, n = 4.

Cultivar	Yield per tree [kg] in different treatments				
	T1	T2	T3	F2	F3
'Samba'	11.2 ± 2.5	13.7 ± 3.3	7.1 ± 2.4	5.9 ± 0.9	7.4 ± 1.2
'Bellise'	7.2 ± 2.2	10.4 ± 1.7	4.1 ± 6.5	5.4 ± 2.0	5.5 ± 0.9
'Rita'	11.4 ± 1.6	16.5 ± 3.4	6.5 ± 2.1	4.2 ± 1.7	6.8 ± 1.6

up to the top (slender spindle), the incident available light was larger in the middle of a tree at a 1.5 m height in all cultivars and treatments than at a 0.5 m height (Table 2a and b). Under the tree crown, incident light was the smallest for cv. 'Bellise' under cover (Table 2a). In the second height, measurements showed similar results to the other cultivars. For all three cvs. and depending on the treatment, the incident light was lower in the north and south of the trees compared to east and west on both measurement heights in the polytunnels T1 an T2, which can be explained by the north-south orientation of the tree rows. The trees without cover (F2 and F3) showed comparable light values for all measurement positions in the canopy. In the hedgerow system under cover (T3), light values were the lowest in all treatments, cultivars and measuring positions (Table 2a and b).

3.2. *Yield per tree of different cultivars and growing systems*

Fruit yield per tree was significantly larger for all three cherry cultivars under cover compared with that in the field confirming the hypothesis of early and stronger solar radiation as a result of recent climate change. For cherry cv. 'Samba', yield per tree in the same planting system and crown structure was doubled (T1 vs. F2) under protected cultivation and nearly tripled for cv. 'Rita' (T1 vs. F2 and T2 vs. F3) (Table 3), i.e. productivity improvements, which cannot easily be obtained by other means such as breeding, fertiliser etc. At the same time, both cultivars generally showed the largest yield under cover compared with cv. 'Bellise'. In the growing system with the widest tree spacing (T2), yield of trees of cv. 'Rita' was larger compared with the

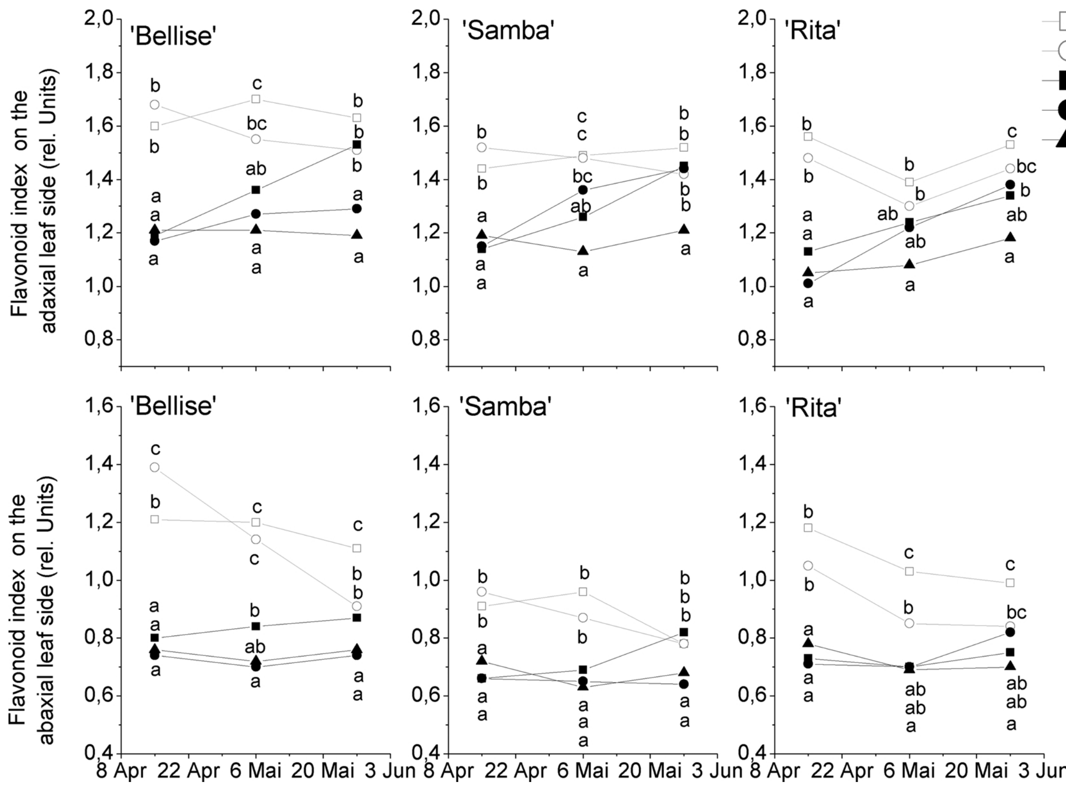

Fig. 1. Flavonoid index on the adaxial and abaxial side ofthe leaves of the tree cherry cultivars 'Bellise', 'Samba' and 'Rita' for different treatments and picking dates. n = 20; different letters denotes significant differences in between the treatments.

other cultivars; for cherry cv. 'Samba', the productivity increased with the density of trees (T3).

3.3. Flavonoid index – light limitation

The overall objective of the study was to investigate, whether different spacing including row and tree distance as well as crown structure (spindle or hedgerow) and light under this spring condition is limited for tree growth and flowering and fruit development. The flavonoid index (Flav), indicative of leaf growth at the beginning of the growing season, was significantly lower on the cherry trees under cover in all three cultivars on both adaxial and abaxial sides of the leaves than outside (Fig. 1). The adaxial leaf sides increased their flavonoid index during the next three weeks in T1 and T2 possibly due to increasing light intensity in May, in contrast with T3, which remained at the same level. In the 'Samba' and 'Rita' cherry cultivars, a further increase in Flav was measured at the last sampling date when fruits were ripe in T1 and T2.

'Bellise' trees showed a significant increase only in the tunnel system T1. In the most dense planting system with hedgerows (T3) under cover, the flavonoid index on the adaxial leaf sides was lower in all three cultivars on the second and third sampling dates. Overall, on the abaxial side of the leaves in the trees with cover displayed the Flavonoid index in the range of 0.70–0.87 for cv. 'Bellise', 0.63–0.82 for cv. 'Samba' and 0.69–0.82 for cv. 'Rita' (Fig. 1).

3.4. Chlorophyll index

The chlorophyll index, indicative of the nitrogen status of a crop, on the adaxial leaf side was significantly affected by the presence or absence of a crop cover. Cherry trees growing under cover showed a larger leaf chlorophyll index at the beginning of the growing season in all three cultivars (Fig. 2). With leaf development, the chlorophyll index increased in all treatments and cultivars. On the second sampling date (6th May), the spindle trees without cover still exhibited significantly low chlorophyll values ('Samba' and 'Rita' values ~27; 'Bellise' ~26), whereas those grown under cover had the highest chlorophyll index ('Samba' ~32; 'Rita' ~33; 'Bellise' ~30). However, the chlorophyll index of the hedgerow trees under cover (T3) differed not significantly to all other planting systems with and without cover (Fig. 2). One exception was observed for cv. 'Rita', where the ChI was significantly different to T2 and both uncovered treatment (F2, F3). During the next 3 weeks, the chlorophyll index increased faster in the uncovered (F2, F3) than in the covered trees (T1–T3), resulting diminishing differences in chlorophyll index at fruit maturity (at the end of May).

3.5. Nitrogen balance index

Throughout the experiment, the nitrogen balance index (NBI) of the cherry leaves showed a similar dynamic as the chlorophyll index (Chl) with significantly larger values (for all three cherry cultivars on the first sampling date: 18–23, second sampling date: ~22–30) in covered (T1–T3) as compared with uncovered canopies (F2, F3) on the first and second sampling date in all three cultivars (Fig. 2) (first date: ~10–12, second date: ~17–21).

3.6. Specific leaf weight

At the beginning of the growing season, the specific leaf weight increased on trees of all three cherry cultivars until the second sampling date, except cv. 'Samba'. Cherry trees of all cultivars grown under cover showed the highest values in the hedgerow system (T3) (153 cv. 'Rita', 163 cv. 'Bellise' and 187 cv. 'Samba') only on the first sampling date. During the growing season, in all cultivars the largest single leaf weights were measured on the second sampling date in the treatments T1 and F2. On the last sampling date, a tendency of smaller specific leaf weights was observed comparing to the second sampling date. On the first two sampling dates, trees from cv. 'Rita' displayed also the smallest

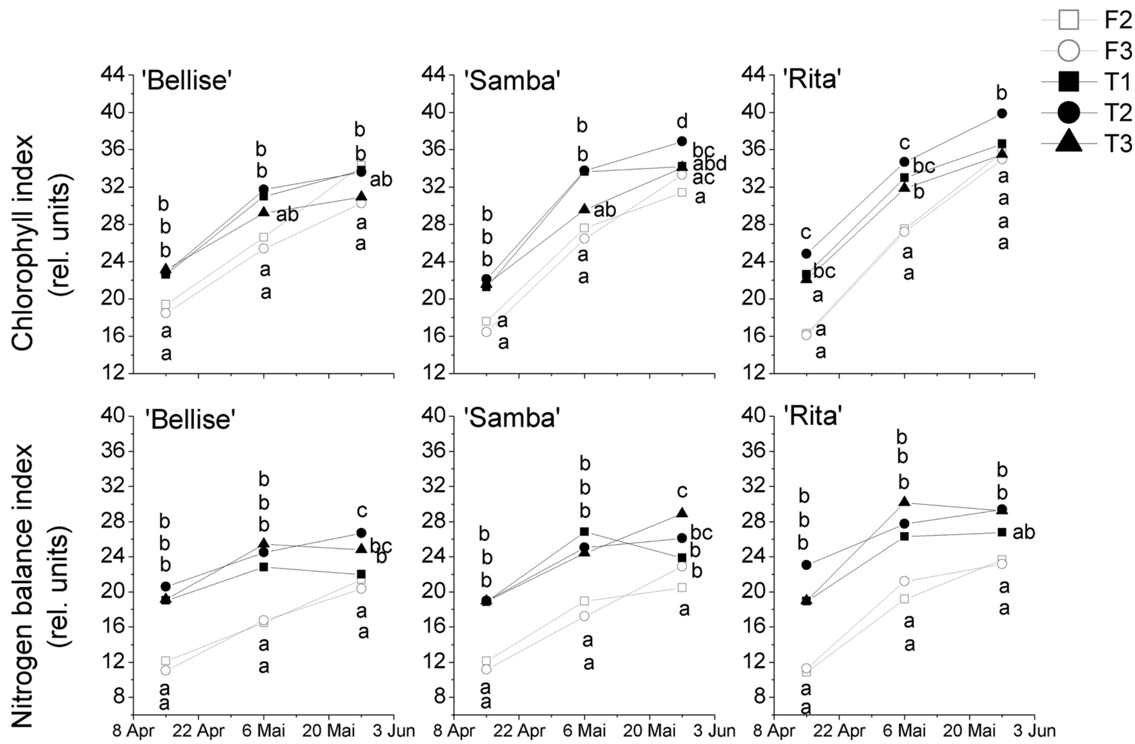

Fig. 2. Chlorophyll index and Nitrogen balance index of the tree cherry cultivars 'Bellise', 'Samba' and 'Rita' for different treatments and picking dates. n = 20; different letters denotes significant differences in between the treatments.

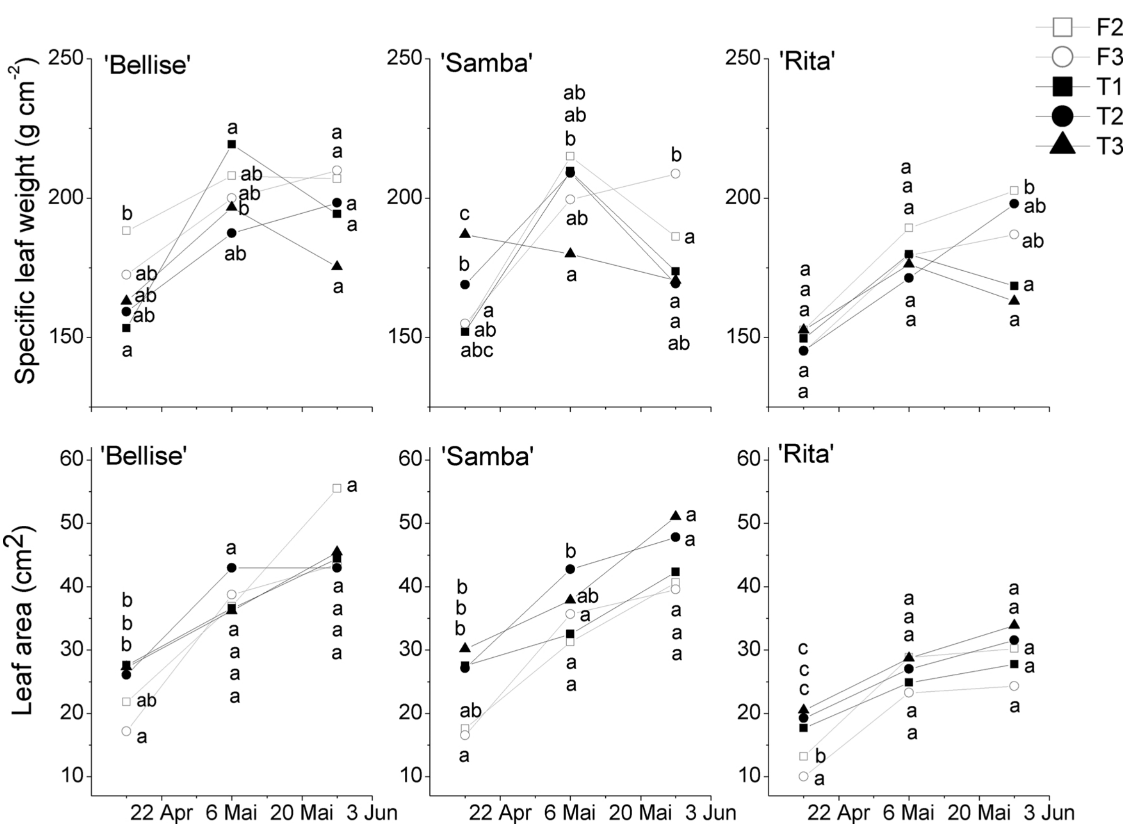

Fig. 3. Specific leaf weight and leaf area of the tree cherry cultivars 'Bellise', 'Samba' and 'Rita' for different treatments and picking dates. n = 4; different letters denotes significant differences in between the treatments.

specific leaf weights (Fig. 3).

3.7. Leaf area

The three cherry cultivars differed significantly in their single leaf area and leaf growth. Trees from cultivar ‘Rita’ displayed the smallest single leaf area throughout the season from 10 cm^2 (F3) on the first sampling date to max. 34 cm^2 (T3) on the last sampling date (Fig. 3). The cover positively affected the leaf area only at the beginning of the experiment. With leaf expansion, the differences in the leaf area were not evident. The largest leaves were observed in cv. ‘Bellise’ and verified between 43 cm^2 (T2) and max. 55 cm^2 (F2) depending on the growing system (Fig. 3). At the beginning of the growing season, trees from cv. ‘Samba’ exhibited single leaf areas from min. 17 cm^2 (F2) to max. 30 cm^2 (T3). On the last sampling date leaves of cv. ‘Samba’ displayed the largest leaf area in the hedgerow system with 51 cm^2 (T3) (Fig. 3).

4. Discussion

4.1. Productivity of the different planting systems depending on light availability

In 2014, the tree yield varied in strong dependence on growing system and the presence or absence of a crop cover. The high yield per tree in T1 and T2 under cover for all three cherry cultivars could be explained by the larger canopy of the trees. Similar results were found by Ozkan et al. (2016) and Robinson (2007) in apple orchards. Robinson (2007) described that tree density had a substantial negative effect on cumulative yield per tree, which is comparable with the results of T3 (high density system) (Table 1). Connor et al. (2016) described a dependency between fruit density, which is necessary for a greater yield, and irradiance within the foliage. The lower light availability in T3 can be one explanatory approach for the lower yield per tree compared with the other two growing systems. Hence, yield per tree of the treatments without cover was lower compared with covered trees. One explanation could be the protective effect against adverse weather conditions, bird damages and the higher temperatures at the beginning of the growing season with a small influence on frost protection.

However, not only the tree density had its impact on yield, also the light availability in the different training systems. Kappel and Quamme (1993), observed in Summerland, BC, that light can be reduced to below 30% in intensive orchards systems (slender spindle and vertical axe). This interaction between orchard productivity and fruit yield as well as total light interception was described in several studies (Wertheim et al., 1986; Wünsche et al., 1996). At the same time, it is well known, that flower development, fruit quality, especially fruit size is reduced by low light levels (Cain, 1971; Jackson and Palmer, 1977). The results of light measurements in trees of cvs. ‘Samba’ and ‘Rita’ grown in T1 and T2 can draw the conclusion that the tree crown is more translucent compared to cv. ‘Bellise’ and let to an increase in light availability as well as the productivity.

4.2. Light interception and its influence on Flav and ChI

Phenolics including the major group of flavonoids are most important groups of secondary metabolites and bioactive compounds in plants (Kim et al., 2003) and their synthesis is highly correlated with light because of their function as UV-protective pigments (Li et al., 1993). A rapid increase in flavonoid biosynthesis is generally observed under high light conditions, which reflects the important role of flavonoids in photoprotection (Schmelzer et al., 1988; Zoratti et al., 2014). First results of Barthod et al. (2007) showed that the Dualex™ derived UV absorbance of leaf epidermis increased significantly with increasing light and the data from the instrument could be a good indicator for the amount of phenolics in the leaves. During the measuring period, the constant flavonoid index on the abaxial leaf side of cherry trees grown under cover can be explained by stronger vegetative growth and less light availability in the tree canopies (Fig. 1 and Table 2). This is reflected in larger single leaf area as well as specific leaf weight (Fig. 3) and trees density (T3) (Table 1). At the same time, the results showed that light availability is reduced under cover, which is evident in a lower Flav in leaves of all three cherry cultivars grown under cover. Generally, the incident light was reduced because of using the cover, which blocked a significant part of UV radiation in the solar spectrum while most of visible radiation is transmitted. At the same time, the polyethylene cover can scatter the remaining transmitted radiation, especially in the shortwave part of the spectrum. Especially the Flav on the adaxial leaf side was the lowest for all three cherry cultivars grown in the high-density system (T3), which is similar to the lowest incident light (Table 2 and Fig. 1). The same tendency can be found for the abaxial leaf side, but the differences between the other treatments under cover were not so pronounced. However, the difference between Flav readings from the abaxial and adaxial leaf side were expected to be negligible and therefore FIav cannot be used as index of light limitation. Evans (1983) described that chlorophyll content highly correlated with nitrogen status in leaves and is associated with the photosynthetic machinery. At the same time chlorophyll should be the important parameter for cultivar selection and phenotyping and can be used to express the potential rate of photosynthesis during vegetation (Cerocic et al., 2012). Our results showed that in all treatments under cover the chlorophyll index is larger than in the field. This allows to draw conclusions regarding to a better nitrogen status and photosynthesis rates especially in T2 for all three cherry cultivars. At the same time, it is obvious that cv. ‘Bellise’ is not suitable for growing in a high-density system (T3) because of the lowest chlorophyll index and in conclusion the lowest yield per tree (Table 3). For cvs. ‘Rita’ and ‘Samba’ the best Chlorophyll index was measured in T2, which resulted in higher yield per tree compared with cv. ‘Bellise’.

4.3. NBI as decision support for a growing system

The Dualex™ was developed by Goulas et al. (2004) in cooperation with FORCE-A to non-destructively measure leaf phenolic content to evaluate a correlation with the nitrogen status of plants. Cerovic et al. (2005) described that phenolics increased under nitrogen deficiency. At the same time, chlorophyll responded in an opposite manner. Cartelat et al. (2005) suggested that the chlorophyll/Phen ratio expressed as NBI was a better indicator for leaf nitrogen concentration as each parameter alone. The results of NBI showed similar values like the chlorophyll index (Fig. 2). At the end of the measuring period, the best NBI for cv. ‘Samba’ was detected in T3 and for cv. ‘Bellise’ in T2 (Fig. 2). A best NBI couldn’t be detect for cv. ‘Rita’ depending on a growing system because of similar results between the growing systems under cover. This result offers the possibility to give a recommendation for choosing one cultivar to grow it under optimal growing conditions.

4.4. Leaf mass depending on light interception

Solomakhin and Blanke (2010) as well as Flore and Layne (1999) described on basis of Sams (1980) PhD thesis that shade increases leaf area with flatter, thinner leaves and more chlorophyll in line with our results of the leaf area as well as the chlorophyll index of the trees under cover (Figs. 2 and 3).

However, the specific leaf weight seems to be unsuitable to assess the different planting systems and to give a recommendation for an optimal growing system because of the missing significant differences between trees grown under cover and outside in the field.

5. Conclusion

Our results have shown that light availability depends on the crown structure and the planting system with special focus on the tree density. Flavonoid index as well chlorophyll index both seem to be good indicators to evaluate the light conditions in an orchard and to give a recommendation for a growing system with high productivity depending on the cultivar.

Covering of cherry trees proved to be a good possibility to protect fruit against adverse weather conditions like heavy rainfall and hail storms, therefore fruit cracking can be minimized and birds can be keep away to ensure yield. At the same time, growers can produce regional products with high quality standards. The evaluation of an optimal growing system depending on the limited light conditions showed the differences between the planting and training systems and that the crop cover with its dedicated plastic film was able to prevent serious light limitations in spring due to straylight.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.eja.2017.11.006.

References

Barthod, S., Cerociv, Z., Epron, D., 2007. Can dual chlorophyll fluorescence excitation be used to assess the variation in the content of UV-absorbing phenolic compounds in leaves of temperate tree species along a light gradient? J. Exp. Bot. 58 (7), 1753–1760.

Cain, J.C., 1971. Effects of mechanical pruning of apple hedgerows with a slotting saw on light penetration and fruiting. J. Am. Soc. Hortic. Sci. 96, 664–667.

Cartelat, A., Cerovic, Z.G., Goulas, Y., Meyer, S., Lelarge, C., Prioul, J.L., Babottin, A., Jeuffroy, M.H., Gata, P., Agati, G., Moya, I., 2005. Optically assessed contents of leaf polyphenolics and chlorophyll as indicators of nitrogen deficiency in wheat (*Triticum aestivum* L.). Field Crops Res. 91, 35–49.

Cerocic, Z.G., Masdoumier, G., Ghozlen, N.B., Latouche, G., 2012. A new optical leaf-clip meter for simultaneous non-destructive assessment of leaf chlorophyll and epidermal flavonoids. Physiol. Plant. 146, 251–260.

Cerovic, Z.G., Cartelat, A., Goulas, Y., Meyer, S., 2005. In-field assessment of wheat-leaf polyphenolics using the new optical leaf-clip Dualex. Prec. Agric. 5, 243–250.

Connor, D.J., Gómez-del-Campo, M., Trentacoste, E.R., 2016. Relationships between olive yield components and simulated irradiance within hedgerows of various row orientations and spacings. Sci. Hortic. 22, 391–403.

Evans, J.R., 1983. Nitrogen and photosynthesis in the flag leaf of wheat (*Triticum aestivum* L.). Plant Physiol. 72, 297–302.

Flore, J.A., Layne, D.R., 1999. Photoassimilate production and distribution in cherry. HortScience 34 (6), 1015–1019.

Goulas, Y., Cerovic, Z.G., Cartelat, A., Moya, I., 2004. Dualex: a new instrument for field measurements of epidermal UV-absorbance by chlorophyll fluorescence. Appl. Opt. 43 (2), 4488–4496.

Jackson, J.E., Palmer, J.W., 1977. Effects of shade on the growth and cropping of apple trees. II. Effects on components on yield. J. Hortic. Sci. 52, 253–266.

Kappel, F., Quamme, H.A., 1993. Orchard training systems influence early canopy development and light microclimate within apple tree canopies. Can. J. Plant Sci. 73, 237–248.

Kim, D.-O., Jeond, S.W., Lee, C.Y., 2003. Antioxidant capacity of phenolic phytochemicals from various cultivars of plums. Food Chem. 81, 321–326.

Legave, J.M., Blanke, M., Christen, D., Giovannini, D., Mathieu, V., Oger, R., 2012. A comprehensive overview of the spatial and temporal variability of apple bud dormancy release and blooming phenology in Western Europe. Int. J. Biometeorol. 57 (2), 317–331.

Li, J., Ou-Lee, T.M., Raba, R., Ammundson, R.G., Last, R.L., 1993. Arabidopsis mutants are hypersensitive to UV-B radiation. Plant Cell 5, 171–179.

Overbeck, V., Schmitz, M., Blanke, M., 2017. Targeted forcing improves quality, nutritional and health value of sweet cherry fruit. J. Sci. Food Agric. 97, 3649–3655.

Ozkan, Y., Yildiz, K., Kucuker, E., Cekic, C., Ozgen, M., Akca, Y., 2016. Performance of 'Fuji' apple on M.9 rootstock in different tree training systems for the first five years. J. Agric. Sci. Technol. 18, 1647–1653.

Pradella, F.M., Peñ-Fleitas, M.T., Gallardo, M., Thompson, R.B., 2014. Evaluation of optical sensor measurements of canopy reflectance and of leaf flavonols and chlorophyll contents to assess crop nitrogen status of muskmelon. Eur. J. Agron. 58, 39–52.

Robinson, T.L., 2007. Effects of tree density and tree shape on apple orchard performance. Acta Hortic. 349, 169–177.

Sams, C.E., 1980. Factors Effecting the Leaf and Shoot Morphology and Photosynthetic Rate of Sour Cherry (*Prunus cerasus* L. 'Montgomery'). PhD Diss. Michigan State Univ., East Lansing, MI, USA.

Schmelzer, E., Jahnen, W., Hahlbrock, K., 1988. In situ localization of light-induced chalcone synthase mRNA chalcone synthase, and flavonoid end products in epidermal cells of parsley leaves. Proc. Natl. Acad. Sci. U. S. A. 85, 2989–2993.

Schmitz-Eiberger, M., Blanke, M.M., 2012. Bioactive components in forced sweet cherry fruit (*Prunus avium* L.), antioxidative capacity and allergenic potential as dependent on cultivation under cover. LWT—Food Sci. Technol. 46, 388–392.

Solomakhin, A., Blanke, M.M., 2010. Microclimate under coloured hailnets affects leaf and fruit temperature, transpirational cooling, leaf anatomy and vegetative and reproductive growth as well as fruit colouration in apple. Ann. Appl. Biol. 156, 121–136.

Tobin, E.M., Silverthorne, J., 1985. Light regulation of gene expression in higher plants. Annu. Rev. Plant Physiol. 36, 569–593.

Wünsche, J.N., Lakso, A.N., Robinson, T.L., Lenz, F., Denning, S.S., 1996. The bases of productivity in apple production systems: the role light interception by different shoot types. J. Am. Soc. Hortic. Sci. 121 (5), 886–893.

Wertheim, S.J., de Jager, A., Duyzens, M.J.J.P., 1986. Comparison of single-row and multi-row planting system with apple with regard to productivity, fruit size and colour, and light conditions. Acta Hortic. 160, 243–258.

Zoratti, L., Karppinen, K., Luengo Escobar, A., Häggman, H., Jaakola, L., 2014. Light-controlled flavonoid biosynthesis in fruits. Front. Plant Sci. 5, 534.